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Creation of energy-efficient and environmentally friendly energy sources on fossil fuels to address global climate issues

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Abstract. For industrialized economies, a strategically important area is developing active methods for industrial use of carbon dioxide emissions to produce marketable products. A rational approach to the problem of clean generation should be based on the complete coordination of the output parameters of the CO₂ discharged from the power plant and the input (working) CO₂ parameters of the consumer, which will reduce the cost of emissions conditioning, and maintain power plant efficiency. The CO₂ parameters from fossil fuel power plants and CO₂ consumers' potential were analyzed for three main indicators most sensitive to power generation: the amount of CO₂, operating pressure, and purity considering the level of technological maturity and market attractiveness. Based on the analysis, three types of energy-industrial symbioses were identified with a cost-effective Power Plant – Consumer model without an intermediate unit for matching input and output parameters of CO₂ (without a CO₂ capture and conditioning system). A hybrid solution combining modern IGCC and the latest thermodynamic cycles based on oxy-fuel technologies is offered as a generalized configuration of the energy part of the promising complex. The concept and key technological solutions of the promising energy-industrial symbiosis "Power Generation Unit – CO₂-based production" are being developed at Ural Federal University. Such symbiosis ensures the low-cost supply of CO₂ to industrial consumers using mineralization technology. It will allow utilizing not only technogenic carbon but also ash, slag, and construction industry waste to produce marketable products (cement, concrete, and other materials).

1. Introduction

In the global energy sector, fossil fuels dominate, producing 61.5% of the world's energy [1]. At the same time, thermal power plants produce ~ 35% of global anthropogenic emissions of carbon dioxide [2], which accounts for about three-quarters of greenhouse gas (GHG) emissions causing climate change in the planet [3].

The Paris Agreement, ratified by Russia in September 2019, requires all parties to halt the growth (reach peak values) of GHG emissions as soon as possible, and then proceed to an absolute global reduction to achieve carbon neutrality in the second half of the 21st century – a balance between anthropogenic emissions of GHG and their absorption, i.e., reduce net GHG emissions to zero.

The commitment to reduce GHG emissions requires developing environmentally and economically viable technologies for CO₂ capture and its subsequent utilization. However, the emission control measures taken so far in Russia are not systematic. They do not rely on a holistic vision of the risks and prospects for the global economy's low-carbon development. The low-carbon strategy formulation in Russia began in 2017. In March 2020, the Ministry of Economic Development of the Russian Federation sent for approval to the Government a Strategy for the Long-Term Development of the Russian



Federation with a low level of GHG emissions until 2050. For industrialized economies, it is strategically vital to rely not only on passive mechanisms of technogenic CO₂ accumulation in natural ecosystems (forests, swamps, seas) [4], but also to develop active methods for industrial use of CO₂ to produce marketable products [5]. Among current methods, a special place is occupied by the new CO₂ capture technologies using industrial wastes (power plant fly ash, metallurgical slag, industrial waste, construction and demolition materials), which is reflected in the Strategy. The Baseline Scenario of the Strategy assumes a large-scale increase in the Russian economy's energy efficiency, full balance of forest reproduction as a natural eco-structure of carbon dioxide sequestration. The target value for the Baseline Scenario implementation is to reduce GHG emissions to 2/3 of the 1990 level by 2030 transiting to the Intense Scenario trajectory and achieving carbon neutrality in the second half of the 21st century [6].

As the main technological direction of the transition to low-carbon development, the Strategy considers several main areas:

- increasing the efficiency of materials use and its recycling ratio, and secondary energy sources utilization;
- technology development for capturing, processing, use, and/or disposal of carbon dioxide emissions from industrial and energy production processes.

It is necessary to implement technologies for capturing and subsequent utilization of CO₂ to solve the energy sector decarbonization problem. This requires a systematic approach, including emissions structuring by volume, parameters, and composition, analysis of the utilization potential for captured CO₂, and development of optimal energy cycles. The final product in such cycles is not only electricity but also technogenic carbon dioxide released in a convenient form for deposition or utilization.

2. Market analysis for CO₂ produced by power plants and its consumption

The specific CO₂ emissions for conventional steam cycle power plants (SubC, SC, USC) or combined-cycle power plants (CCGT, IGCC) with a spread in a net efficiency of 35-60% vary from ~ 2.8 up to ~ 8.0 Mt CO₂ / (GW · year) depending on the fuel type, operation mode, and technology variability (figure 1) [7- 9]. The corresponding gross emissions from the advanced high-capacity power plant (USC, AFBC, CCGT, IGCC, Oxy-fuel combustion) are 3.75-4.47 MtCO₂/year for ~ 660 MW(e) net power [7]. For the most common SC and SubC coal-fired power units with ~ 300 MW(e) net power, gross CO₂ emissions vary from 1.8 to 3.2 MtCO₂ /year.

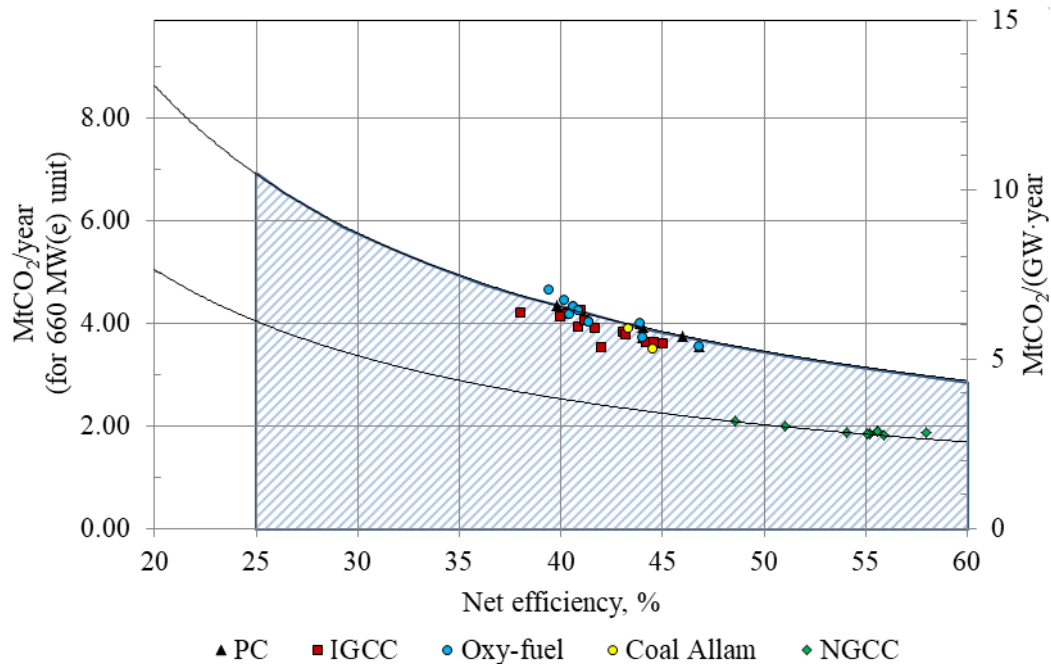


Figure 1. Power plant net efficiency and CO₂ emissions.

Achieving the goals in terms of CCUS (carbon capture, use, and storage), i.e. 90-99% CO₂ capture with a plant net efficiency higher than 50%, cannot be fulfilled considering just a separate power unit as the object of the study, since this is a complex combination that includes a solid fuel power unit and systems of extraction, utilization, and deposition of technogenic carbon. In such a system, CO₂ from the power plant is theoretically fully supplied to the consumer.

The rational approach to the problem of clean generation solution is based on a clear understanding of the complete interconnection of the power plant output CO₂ parameters (Q_1 , P_1 , T_1 , R_1) and consumer CO₂ input (operating) parameters (Q_2 , P_2 , T_2 , R_2). If these conditions are met, it is possible to reduce the power plant operating expenses on the carbon dioxide coupling unit and achieve the power plant efficiency with CCUS closer to one without CCUS.

Elements of the Life Cycle Assessment (LCA) system [11] provide a reasonable approach for the optimal power plant profile and market capacity selection and the best technological routes development. Such routes meet new requirements and are based on the analysis of technologies for the clean production of electric and thermal energy from fossil fuels (figure 2).

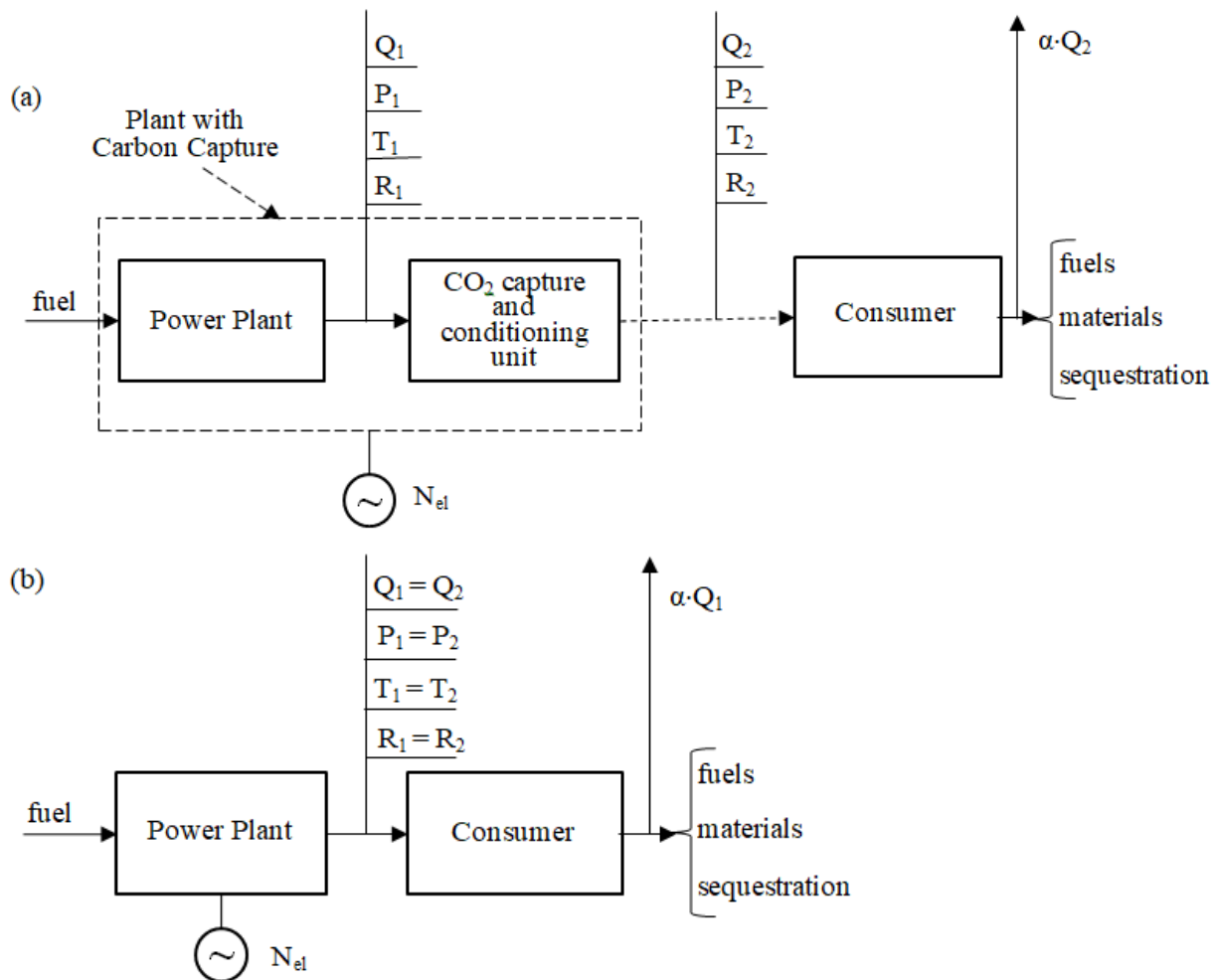


Figure 2. CCU: (a) traditional approach; (b) forward-looking approach. Parameters: volume (Q), pressure (P), temperature (T), and purity (R).

The potential market for technogenic carbon includes two main sequestration directions for captured CO₂: industrial use and geological (underground) or ocean disposal. Most of these directions, as a rule, impose very sensitive technical requirements to anthropogenic carbon in terms of volume, pressure, and purity [12]. The formation of these parameters is determined by the legal framework, market demand, and the internal logic of the technology development.

The distribution of CO₂ consumption by the refining process operation pressure is very complex, significantly overlapping the energy sector pressure ranges [12, 13, 14]. Identification of weight coefficients for pressure sub-ranges and CO₂ purity allows assessing the potential demand for existing and developing methods for CO₂ removed from power plants to the industrial sector and determining the framework requirements for the newly designed CCUS energy technologies system [14].

According to the conservative technological scenario (RTS - Reference Technology Scenario), with an average annual CO₂ growth rate of 1.7%, CO₂ consumption could reach 296 MtCO₂/year by 2030 and 491 MtCO₂/year by 2060. With the use of new technologies for CO₂ conversion to different products (fuels, chemicals, construction materials), as well as with the development of new Oxy-fuel energy systems based on supercritical carbon dioxide (sCO₂) the global potential for industrial use of CO₂ could increase significantly from 1 up to 7 GtCO₂ / year by 2030. Of the new recycling technologies [15] mentioned above, the group of building materials production based on industrial waste's carbonization is the most appropriate for the emissions reduction, since it is the most suitable for this purpose because:

- the final carbonization product is significantly more stable than other CCU technical applications;
- the production of building materials based on carbonization is less energy-intensive than fuels and chemicals, which require a large amount of hydrogen;
- waste-based materials have high consumer properties, lower cost than conventional production, and avoid expenses on waste disposal procedures.

The mineralization technologies are developed in two directions - ex-situ and in-situ.

The success of symbiotic energy complexes using ex-situ technologies depends on the choice of raw materials, which are the source of active Ca and Mg. Currently, two types of mineral raw materials are being considered. These are natural rocks-minerals (olivine, wollastonite, serpentinite, phlogopite) and artificial materials – alkaline production wastes (fly ash, power, and metallurgical slags, waste cement and concrete, etc.) [16].

In the minerals, Ca and Mg are partly inactive being in the form of silicates - chemical compounds with SiO₂. The other part of these elements, not bound in the structure of the silicon dioxide tetrahedron, is free and reactive. After isolation from the mineral mass, this part of Ca and Mg is ready to react with CO₂ to form solid CaCO₃ / MgCO₃. The process proceeds at high pressure and temperature (figure 3).

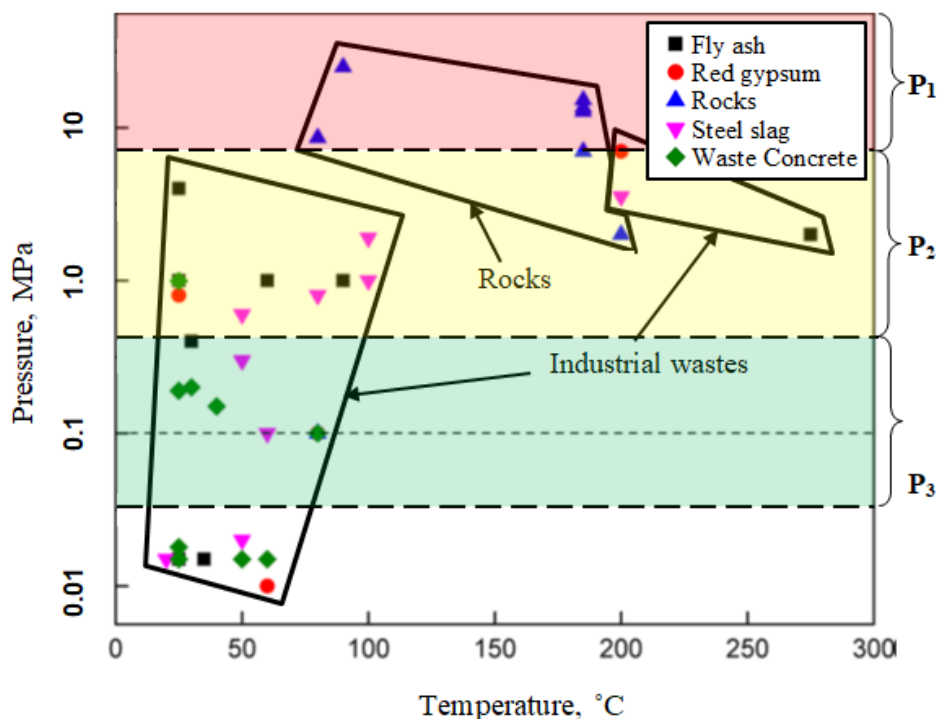


Figure 3. Carbonization conditions for different materials.
(The figure is based on the data given in [12]).

Artificial materials are more suitable for CCU. Before entering a CCU system, they are usually subjected to a high-temperature heat treatment in the main production line (boilers, furnaces, etc.), which converts them from crystalline to amorphous state and reduces bonds strength. As a result, while carbonization of rocks usually requires high pressures and elevated temperatures, the carbonization of artificial materials can be carried out at low (including atmospheric) pressure and temperature (figure 3). The low-temperature process for industrial wastes is of interest to the technology being developed. The potential of CO₂ consumption by alkaline industrial waste residues is estimated at 80 Mt CO₂/year [17] up to 200–300 Mt CO₂/year [18]. For Russia, this potential can be approximately 1.5–4% of the global one, which corresponds to CO₂ emissions from coal generation in Russia.

A common disadvantage of ex-situ technology is the relatively low percentage of CO₂ capture during the carbonization process. For example, CO₂ emissions could be reduced by 2-3 % during the interaction of flue gases with fly ash at the power plant [19].

3. Classification of power plants by parameters of emitted CO₂

The coordinated analysis of CO₂ parameters from the power plants and the potential of CO₂ consumers is carried out based on three main indicators most sensitive to the power generation process: volumes (Q), operating pressure (P), and purity (R).

Parameters of CO₂ streams in distinct output pinch points from the power plant are given in table 1.

Table 1. Control indicators of CCU processes.

Level	Parameter		
	Q, MtCO ₂ /year	P, MPa	R, %
1	<2,5-4	>7(8)	90-99,9
2	5-50	0,5-7(8)	15-90
3	>50	<0,3-0,5	<15

* Here and further the technology advantages marked with red (lowest) – yellow (medium) – green (highest).

The considered power plants can be divided into three groups by parameters of CO₂ flows (figure 4):

A – low-pressure P₃, low purity R₃. Such parameters are typical for CO₂ in flue gases (products of fuel combustion with air) in the most power plants (pulverized coal power units, IGCC without CCS and with air-fuel GTU at standard parameters, as well as NGCC);

B – low-pressure P₃, high purity R₁. Such output CO₂ parameters are characteristic to Oxy-fuel combustion units and the pre-combustion IGCC system with Oxy-fuel GTU at standard parameters;

C – average and high-pressure P₂/P₁, high purity R₁. Such outlet CO₂ parameters are peculiar to IGCC with new Oxy-fuel and high-pressure s-CO₂ GTU.

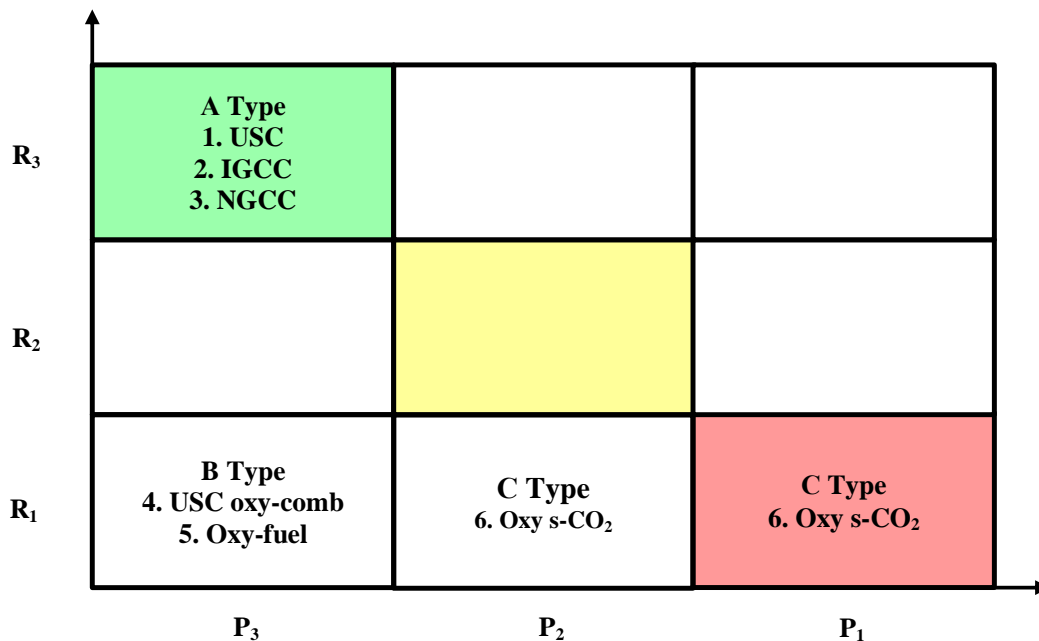


Figure 4. Classification of heat and power generation technologies by emitted CO₂ pressure and purity.

4. CO₂ consumption rates in individual industries

The CO₂ consumption technologies group distribution is shown in figure 5 according to the pressure and purity level of the consumed CO₂.

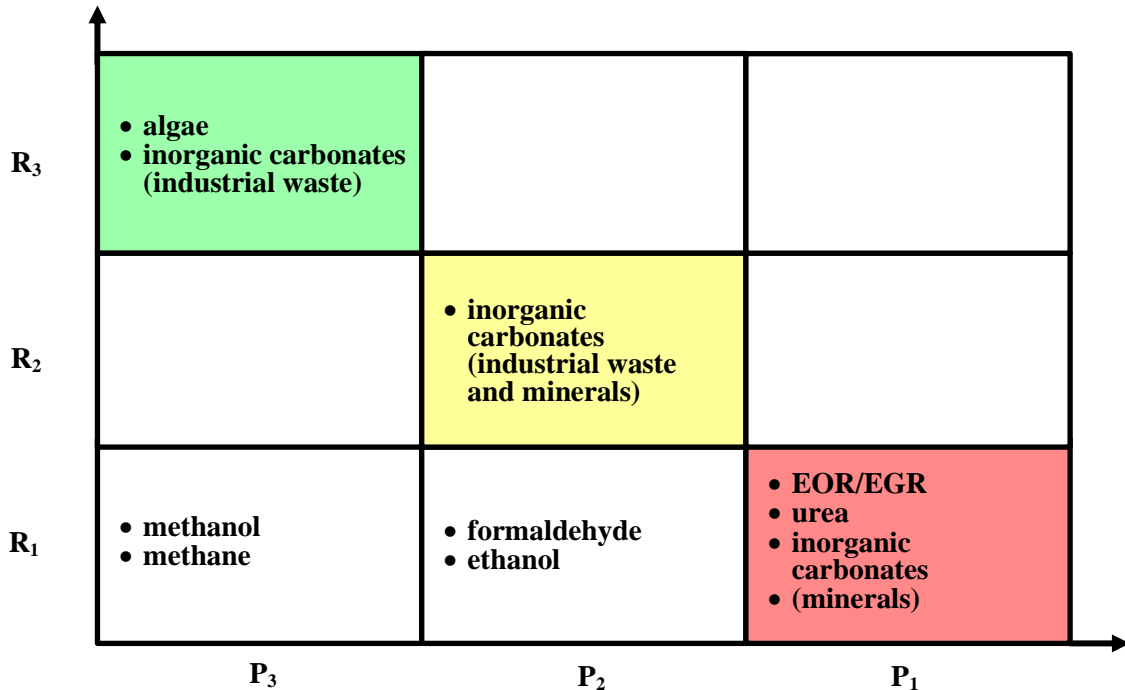


Figure 5. Classification of high-performance Q₃ utilization technologies by CO₂ pressure and purity.

Figure 5 shows that the considered utilization facilities in terms of pressure and purity of the consumed CO₂ can be divided into groups, mainly corresponding to the groups of power plants (further in the text maximum expected forecast values are given in brackets):

A – low-pressure P₃, low purity R₃ with a volume of 144.1 (930) MtCO₂/year;

B – low-pressure P₃, high purity R₁ with a volume of 3089 (4300) MtCO₂/year;

C – medium and high-pressure P₂, P₁ and high purity R₁ with a volume of 319.2 (585.2) GtCO₂/year.

The total potential for CO₂ utilization is 3.6 (5.8) GtCO₂/year, or about ~35 (60) % of global CO₂ emissions from coal-fueled energy generation.

Based on the above data, three types of energy-industrial symbioses can be formed (figure 6), working according to the low-cost model shown in figure 2b.

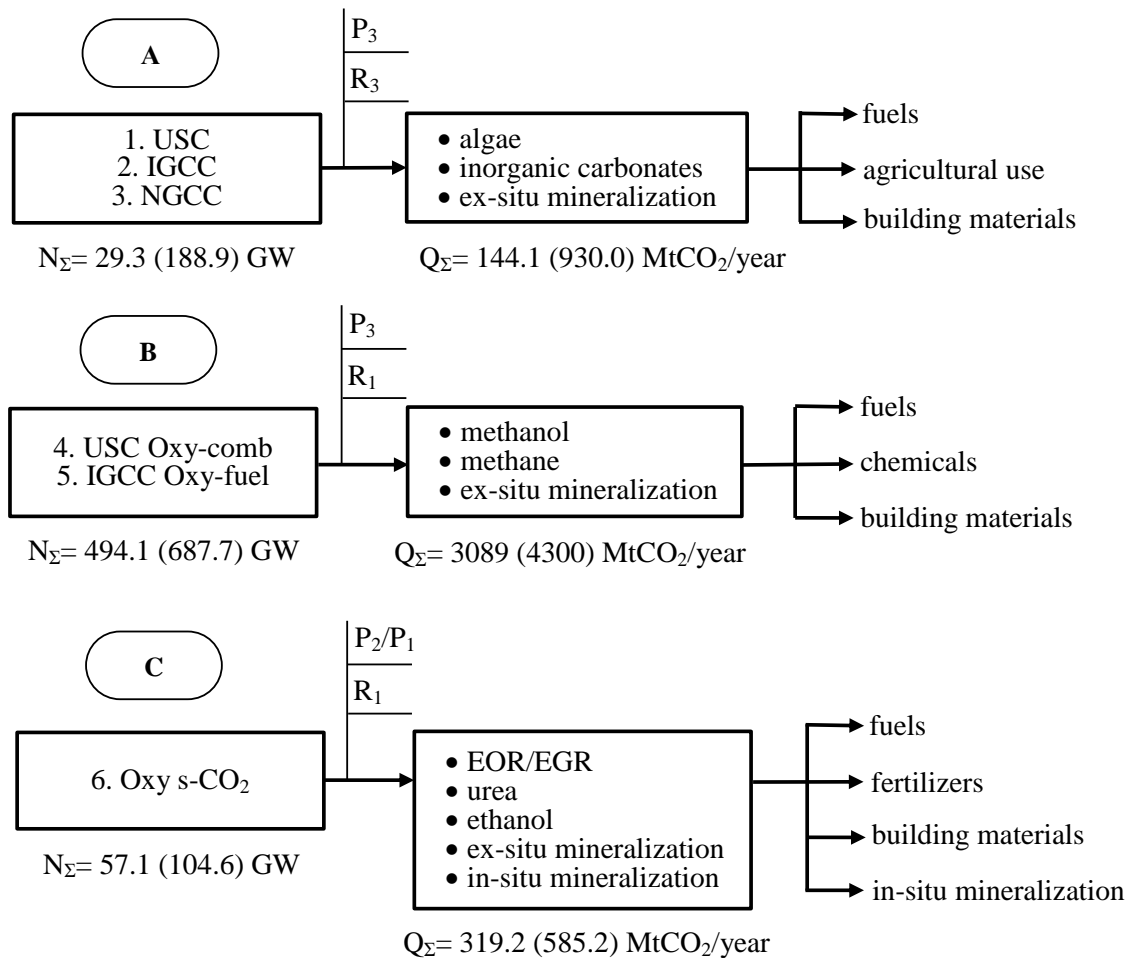


Figure 6. Types of low-cost energy-industrial symbioses.

The total potential of low-cost energy-industrial CCU symbioses reaches 580.4 (981.3) GW, comparable to the installed capacity of coal power plants in China. For Russia, the potential of low-cost technologies may match the coal power generation.

Conclusions

The paper reflects an analysis of the operating power plants from the BAT list (Best Available Techniques) [20] and its Russian analog [21], extended with the latest promising developments of Oxy-fuel IGCC and 18 main technologies of industrial production based on CO₂ consumption from the list of IEA [15].

The analysis has revealed three types of energy-industrial symbioses, operating under the low-cost Power Plant – Consumer model without an intermediate coordination block of input and output parameters of CO₂ (without the CO₂ capture and conditioning system) without a noticeable loss in the initial energy efficiency.

The symbiosis of type A includes the mass group of traditional power plants (pulverized coal power plants and NGCC) and IGCC without CCS and with GTU of standard parameters, as well as new large-scale production with low requirements for pressure and purity of CO₂ (production of building materials based on carbonization of artificial materials, such as ash, slag, waste cement, and concrete, as well as bio-fixation technology).

The symbiosis of type B includes Oxy-fuel power units and Oxy-fuel IGCC with GTU of standard parameters combined with large industries characterized by low CO₂ pressure requirements and high demands for CO₂ purity (methanol, methane production).

The symbiosis of type C includes power plants with the latest developments of Oxy-fuel GTU with high-pressure s-CO₂ combined with a large list of various production facilities based on pure compressed CO₂, where the main place occupy production technologies for mineral fertilizers, fuels, in-situ mineralization, and EOR/EGR.

A hybrid option combining technological solutions of modern IGCC and the latest thermodynamic cycles based on oxy-fuel technologies was adopted as a generalized configuration of the energy part of the research object. The configuration of the energy block (a type of thermodynamic cycle) depends on the type of the technological part: the level of pressures and temperatures appropriate to the cycles and working fluids (binary Brighton+Rankin or Rankin cycle); turbine with an air (Air-fuel) or oxygen (Oxy-fuel) oxidizer; working fluid of the gas turbine (mainly air/steam, steam, steam, and carbon dioxide). The operation of the turbine unit driven by the media with significantly different compositions (the main component – N₂, or CO₂, or H₂O) leads to the necessity of working cycle parameters re-assignment and turbine unit elements re-design.

The proposed concept for the development of energy-efficient ecologically clean energy units within the framework of Russia's long-term development strategy, the National project "Ecology", housing renovation program, etc. allows for a more comprehensive approach addressing global and regional problems of society.

The Ural Federal University is developing the concept and key technological solutions for a promising installation, an energy-industrial symbiosis "Power Generation Unit – CO₂-based production" that provides low-cost CO₂ supply to industrial consumers. Such integration, which uses mineralization technology, will make it possible to utilize CO₂ and waste in the form of ash, slag, and construction waste with the production of commercial products (cement, concrete, etc.). Some of the results are presented in [23–34].

Acknowledgments

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